Digitizing Wildlife: The case of reptiles 3D virtual museum

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***Abstract*—In this paper we design and develop a 3D virtual museum with holistic metadata documentation and a variety of reptile behaviors and movements. First, we reconstruct the reptiles mesh in high resolution, and then create its rigged/skinned digital counterpart. We acquire the movement of two subjects using an optical motion capture system, accelerometers, and RGB-vision cameras; these movements are then segmented and annotated to various behaviors. The 3D environment, VR and AR functionalities of our online repository serve as tools for interactively educating the public on animals, which are difficult to observe and study in their natural environment. It also reveals important information regarding animals' intangible characteristics (e.g., behavior), that is critical for the preservation of wildlife. Our museum is publicly accessible, enabling motion data reusability, and facilitating learning applications through gamification. We conducted a user study that confirms the naturalness and realism of our reptiles, along with the ease of use and usefulness of our museum.**

INTRODUCTION

Modern times tend to demand a lifestyle which causes people, especially the youth, to become more and more disconnected from nature. The busy schedules and fast pace of everyday life in the age of information, has alienated us from nature and neglecting the environment. On top of that, habitat loss/fragmentation, deforestation, and climate change, caused by the global rise of urbanization seriously threaten the survival of wildlife [1] Therefore, now more than ever, there is a need to record and digitize the earth's wildlife, significantly benefiting the preservation of the species. Recent technological advances offer great opportunities to bring nature closer to our homes, bridging the gab between artificial and natural world, thus allowing us to study, analyze and familiarize ourselves with the fauna [2]. Inspired by this, there is a need for systematic documentation of wildlife and so, over the last decade, there has been some interest to design and develop 3D virtual museums/zoos, or other educational and scientific tools, that store and visualize digital exhibitions of wildlife.

A virtual museum is a collection of digital data, presented in an intuitive and informative manner. Virtual museums serve as counterparts to physical museums, replicating or even enhancing the experience of their visitors. Similar to traditional museums, virtual ones aim to offer knowledge to the public through their captivating exhibits and the organization of their display [3]. They also enable closer observation of the exhibits which can reveal information, important to their long-term preservation, especially in the case of virtual zoos [4]. Unlike physical museums, the multi-media capabilities of virtual ones unlock a new range of functionalities. As the cost of Virtual Reality (VR) headsets goes down, they are accessible to a wider range of people, including secondary students or students with disabilities. Being accessible worldwide, a virtual museum offers interactive and personalized experiences to the visitor, previously impossible due to preservation and safety concerns.

In particular, virtual museums for wildlife exhibitions have become increasingly popular, with influential institutions such as Natural History Museum[1] in London, and the University of California Museum of Paleontology[2] in Berkeley, holding online tours for some of their displayed specimens. Equally important, is the ability to share and exploit the informative power of existing databases by allowing access, like the Joconde database maintained by the French Ministry of Culture. Nevertheless, previously developed virtual museums often portray their animals in static 2D poses. Developing 3D mesh of animals, though, can significantly improve the educational impact of such museums, as they allow a closer and more careful observation of the specimens. Methods such as photogrammetry are heavily used to produce 3D meshes of real, captured animals. A primary example is the work of Digital Life 3D[3], scanning a wide range of animal species accurately and with high quality.

Apart from 2D/3D static poses, there is also a need to display moving animals. Attempting to create a 3D version of such movement, instead of the currently used 2D videos, is essential to acquiring a well-rounded knowledge of their nature. With the recent development and motion capture technology, and the new release of powerful graphics cards, we are able to learn about their behavior and intangible characteristics. So far, intangible characteristics of wildlife have been preserved mostly via documentaries such as National Geographic[4], Animal Planet[5] and BBC WildLife[6], which are still considered as the primary methods for recording and visualizing animal behavior for scientific and educational purposes. However, 2D documentaries do not facilitate in-depth analysis and reproduction of their motion (e.g., skeletal geometry, behavior), giving rise to motion capture technologies.

Key-framing approaches, despite of their popularity in animated films, were later on discarded due to their time-consuming nature and the level of expertise needed to be implemented. Key-framing approaches still suffer in terms of the realism of produced motion and ability to capture subtle, secondary movements. Alternative methods have been then employed such as hiring actors to imitate animals behaviors, or the use biomechanical simulations. Even though these simulations give control to the animator, achieving a certain level of species-specific realism, motions and behaviors are still not authentic. Employing motion capture systems enables the documentation of intangible aspects of the animals' nature as opposed to the tangible aspects attained by tra-

[1] https://www.nhm.ac.uk/visit/virtual-museum.html
[2] https://ucmp.berkeley.edu/
[3] http://digitallife3d.org/3d-model
[4] https://www.nationalgeographic.com/animals
[5] https://www.animalplanet.com/
[6] https://www.bbc.co.uk/programmes/p08dlvg1

ditional methods, leading to revelations about animal behavior, previously unexplored. However, capturing animals is a particularly challenging task due to their uncontrollable and unpredictable nature. Previous work on motion capture was successful in documenting movements and behaviors of well-trained primates, relatively large land mammals, and easily confined insects [5]. Despite that, little attention has been devoted to acquiring the 3D movement of species such as amphibians and reptiles, that will enable the implementation of interactive educational and scientific tools with remarkable accuracy and realism.

In this work, we focus on reptiles, which have several peculiarities in relation to other animals. They move in a more complex way, which differs from human-like motion, making it significantly harder to replicate their movements' style and behavior. In addition, their small size, sharp, and specific movements makes the task of capturing reptiles more challenging. Despite that previous works in experimental biology provided outstanding tools for the 3D reconstruction of animals, including reconstruction of animal's 3D skeleton from still cameras [5], as well as from museum collections [6], broad universal applications are in need. For the case of reptiles, even though X-ray reconstruction of moving morphology (XROMM) provided highly detailed 3D reconstructions of well-defined movements, such as rib kinematics during breathing and joint mobility [7], [8], herpetologist are still relying on species morphology and behaviour from databases providing pictures of the species in static poses, e.g., "The Reptile Database[7]", the "Australian Reptile Online Database[8]" or the database for the closely related group of Amphibians, the "AmphibiaWeb[9]". Only recently the value of 3D scanning methods and their ability to represent high-quality, accurate, shareable, and (typically) complete 3D visualizations of live specimens in the field or the laboratory have been highlighted ([9], [10]), but yet do not portray animated behaviors.

We design and develop a publicly accessible 3D virtual museum, that stores 3D animated avatars of reptiles in exceptional quality and realism, and we provide holistic documentation and metadata information. We present the complete pipeline of reptile digitization, modelling, and capturing: using photogrammetry, we reconstruct the reptiles' mesh and texture [10] in high resolution. The same subjects have been motion captured utilizing three different technologies: optical motion capture, accelerometers, and RGB-vision cameras. The reconstructed meshes are then skinned and rigged, and the acquired motion has been baked to achieve natural and realistic animation. The movements are then segmented and labelled accordingly, in close collaboration with expert biologists. For the purposes of this study, we use two reptile species found in Cyprus (snake and lizard) as our case study. To evaluate the impact of our museum as educational tool and gain insight as to how information is more easily transmitted, we conducted a user-study. As demonstrated in our experiments, our work can be projected and displayed onto a 3D, virtual (VR), and augmented reality (AR) environments, plus a holographic pyramid. Such virtual representation provide the users with more informative, educational, and interactive experiences. More specifically, our contribution is fourfold: (i) we describe the complete pipeline for motion capturing reptile behaviors; (ii) we identify the metadata types necessary to holistically gather information about reptiles and integrate the identified types to a metadata schema; (iii) we deliver an online 3D digital museum that comprehensively stores 3D animated reptile models, labelled with authentic behaviors, allowing people to visualize 3D scenes with remarkable clarity and realism; and (iv) we carry out a user-study to evaluate the impact of our 3D virtual museum, and the provided educational and scientific tools, in terms of ease of use, usefulness, learnability, engagement, and interactivity.

This work paves the way for various applications and extensions, such as educational tools and games that may attract the interest of the younger generations. Additionally, our work provides the basis for in-depth analysis of reptiles' behavior in their natural environment. Understanding and observing the motion and behavior of an animal without the need for visual monitoring in the field, through the development of behavior recognition algorithms, can offer sub-

[7] http://www.reptile-database.org/
[8] https://www.arod.com.au/
[9] https://amphibiaweb.org

stantial assistance to researchers with numerous applications in the biology domain (e.g. wildlife monitoring and conservation).

RELATED WORK

In this section, we review past work on the evolution of Virtual Museums, including currently available animal databases, and we present the current state-of-the-art techniques for animating animals and reptiles.

Virtual museums and animal databases

Virtual museums are digitally spatial entities that retain the general characteristics of a physical museum, in order to complement, enhance, or augment the museum experience. This is achieved through navigation of virtual objects/subjects, richness of content, user personalization, and interactivity. Virtual museums are located in the World Wide Web as an online exhibition, and they digitally reconstruct real places, subjects and/or acts in a natural way [11]. Over the last couple of decades, various museums make great efforts in digitizing their tangible artifacts by creating 3D virtual equivalents, so as to enhance the physical presence of their visitors or to enable exclusive web browsing as a unique experience [12]. Visitors can highly benefit from these 3D environments through a series of virtual interactive activities (explore, communicate, interact, and modify the digital subjects). Indeed, additional functionalities, such as augmenting the 3D environment in an AR manner, enrich the learning experience of visitors. Especially over the last decades, even though AR is not a recent technology, affordable portable electronics constitute AR as a profound educational tool and valuable research assistant (e.g., [13]), thus complementing the educational impact, when used in the context of virtual museums. Considering this, virtual museums and exhibitions have become very popular, mostly exhibiting tangible cultural heritage artifacts [14], or more recently, intangible cultural creations [15].

Despite the increasing popularity of such online repositories, in the context of wildlife, very little effort has been devoted to the development of virtual museums or zoos [3]. Many scholars in the past digitize animals and reptiles using photogrammetry [9], [10], to achieve a high resolution, faithful representation of the subject's texture and shape. A great example is the Digital Life 3D[10] repository, which portrays accurate 3D models of various species. Other digital repositories include SketchFab[11], or the Truebones[12] databases. However, these recordings are mainly static, and when animated do not involve the actual movement of specific behaviors of the recorded wildlife, except for a few simulated movements which were done by a graphic designer using keyframes. To the best of our knowledge, there are no digital repositories currently available that store authentic animated virtual models of animals with enhanced data, e.g., motion capture, acceleration, and RGB-vision recordings; labeled behavior; metadata information etc. In terms of reptile documentation, there are only few online repositories e.g., the Australian Reptile Online Database, The Reptiles Database[13], and the IUCN Red List[14] that describe details about different species, but only portray images or videos of the animals. In contrast, our work differs from these databases since it creates a comprehensive, publicly accessible database of reptiles (starting from the Cypriot species as case studies, and consequently continue with species from other countries), which stores their movements and various behaviors. Apart from the data itself, we provide a systematic schema to holistically describe the content, e.g., size, global distribution, ecology, diet, reproduction habits, plus other important information about the species.

Motion Capturing and Simulation

Motion capture is a popular technology that is commonly used to record, store and visualize human performances since such systems acquire, by default, movements and behaviors with great realism and naturalism [16]. However, very little effort has been devoted to the digitization, visualization, and analysis of animals [17]. This is mainly due to difficulties in capturing, lack of training (animals sometimes behave aggressively and unpredictably), or their size. A common practice is to motion capture human actors that

[10] http://digitallife3d.org/
[11] https://sketchfab.com/
[12] https://truebones.gumroad.com/
[13] https://reptile-database.reptarium.cz/
[14] https://www.iucnredlist.org/

imitate the movement and style of the subject, and then retarget their motion to a virtual character. For instance, in the famous trilogy of "The Planet of the Apes", the actors had to imitate apes using short crutches, to look as similar as possible to an ape-like style. Even though the movement seems natural, it is not an authentic movement for that subject; note that, in some movies/games, it is preferable to have a humane demeanor and complexion. Another way for animal motion and pose reconstruction is the use volumetric fitting algorithms (e.g., [18]), at the cost of lower accuracy. In that manner, most of the previous attempts have been made to physically simulate the movement of the animals e.g., articulated subjects that have been extinct [19]. More recently, deep learning algorithms have been used to simulate the movement of quadruped animals, e.g., dogs [17], or physically-based reinforcement learning to animate birds [20] or other soft creatures [21]. Despite that, these methods hugely rely on big data for training the networks, and the missing link is the access, and more specifically the acquisition of such data. This is even more complicated and challenging when it comes to small articulated reptiles or insects; mainly due to their small size. So far, most of the effort has been devoted to simulating these movements [22], [23]. However, simulations do not reflect the actual movement of the subject so as to lead to the study and the understanding of their behaviors, or to develop algorithmic ways for automatic identification and recognition of their actions. Currently, only few efforts have been made relevant to motion capturing small reptiles e.g., [24], while only focusing on movement responses, or control using soft-body simulation. In this work, we present a systematic framework which comprehensively records, documents, stores and portrays 3D reptile models and behaviors.

3D REPTILE DATABASE

This section provides an insight into the criteria and information needed for the creation of a reptile's database. Reptiles move in rich and diverse ways, requiring a wide range of metadata information to be fully defined, including descriptive and structural metadata, and the multimedia recordings. In close collaboration with herpetology experts, we identify and present such information which is essential for archiving, presenting, analyzing, and re-using reptile's data, and vital to provide a basis the construction of a digital 3D reptiles repository.

Metadata

Users determine and collect certain metadata types as a means of locating information, discovering resources, and allowing further studies e.g.: content-wise and structure-wise. The objective is for metadata to be utilized for electronic resource organization and preservation of digital resources and information. The established opinion among both professionals and users is that it is essential for metadata to be accessible, interpretable and preservable, as well as assist in archiving, disseminating, studying, and reusing of information [25].

The information found in metadata is compact and basic such as the purpose, means of creation, and timestamps of recordings, which facilitates working with the recorded data. In general, metadata can be divided into distinct main types, namely *descriptive, structural, administrative, reference, statistical* and *legal* metadata [26]. Information about the resource is contained within descriptive metadata, useful for identification and discovery, while information regarding containers of data, and how to manage a resource, are put in the structural and administrative metadata types, respectively. Reference and statistical metadata are used for statistical analysis, the former describing its contents and quality, and the latter the methods for collecting, processing, and producing statistical operations. Lastly, legal metadata is concerned with copyright, creator, and licensing information.

The metadata we record and include in our database can be categorized into four groups. Firstly, we include general information of the species which among others contains its name, global distribution, diet, behavior, as well as the conservation status of the species. The second category holds metadata specific to the studied animal, like its gender, age group, size (body-part lengths), and captured location. Metadata reflecting acquisition information, such as location and date of the 3D scanning and capturing is stored into another category. Finally, metadata regarding the technology used for acquisition, such as the motion capture system and the kind

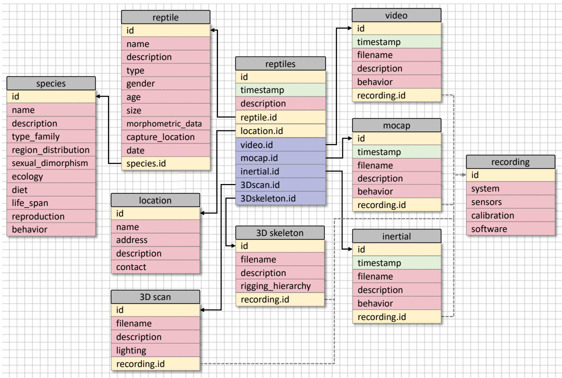

Figure 1. Database schema illustration for holistically describe metadata.

of sensors used, the calibration parameters, and the recording software are collected in the fourth category. In addition, it is important to document metadata information about the environment where the reptile's motion was captured. Such metadata include the location, the size of the environment, other objects used in the scene, as well as the lighting conditions. All these metadata information allows us to study each parameter of the reptile's movement and behavior holistically. They also contribute to understanding the mechanics of capturing motion, and are particularly useful for further biological studies e.g., common behaviors in different species, behavioral variations in different habitats.

Holistic schema

After identifying the important metadata information, an ontological and metadata representation is defined to systematically and structurally organize them among their corresponding recorded data. A holistic database schema is created, as illustrated in Figure 1, which is a logical plan that shows the relationships between metadata elements, and may enable further investigation, studies, and research of the stored 3D reptiles.

DATA ACQUISITION

The initial steps for the development of a 3D reptiles virtual museum rely on building accurate 3D animated models. This can be achieved by scanning the mesh of each of the reptiles, preparing the articulated model, motion capturing, and baking their actions in the corresponding model. This section describes analytically the pipeline for reptile documentation, using as case study two Cypriot reptiles: a snake (*Dolichophis jugularis*), and a lizard (*Stellagama stellio*).

Geometry and mesh modeling

The first step of reptiles model reconstruction is to scan their meshes, in the form of point clouds, using photogrammetry. In this subsection, we describe the method we followed for scanning the animals, including the rigging, skinning and texturing operations.

Scanning In this work, the reptiles were scanned using Beastcam© technology, in close collaboration with the team of Irschick *et al.* [10]. This procedure includes taking multiple photos of the live animals at varying angles. Using a rotating grit bearing photo camera, the reptile is captured within a time window of a few seconds yielding more than 100 pictures. Then, we use photogrammetry, a common technology used for reconstruction to identify similar patterns between the recorded set of photos. Note that, a consistent and balanced lighting along with the need to maintain animals as still as possible, is of utmost importance. Even the smallest movement of the animal results in re-initiating the scanning procedure while overexposure of lighting at parts of the body leads to difficulties in reconstructing an accurate polygon mesh [9]. Using the COLMAP[15] software, the 3D point cloud of the scanned animal is reconstructed. Note that there were cases of slight movements on a part of the animal's body like the head. In such instance, it is required to digitally detach those parts from the body by masking it out, thus producing separate 3D point clouds. The point clouds are then converted into polygon meshes using Poisson Surface Reconstruction, via MeshLab[16]. Figure 2 (top) shows the 3D point cloud mesh of the lizard, and Figure 2 (bottom) the rendered reconstructed model of the snake.

Rigging, skinning and texturing Finally, we develop the corresponding 2D texture files of the scanned animals, again through MeshLab.

[15] https://github.com/colmap/colmap
[16] https://www.meshlab.net/

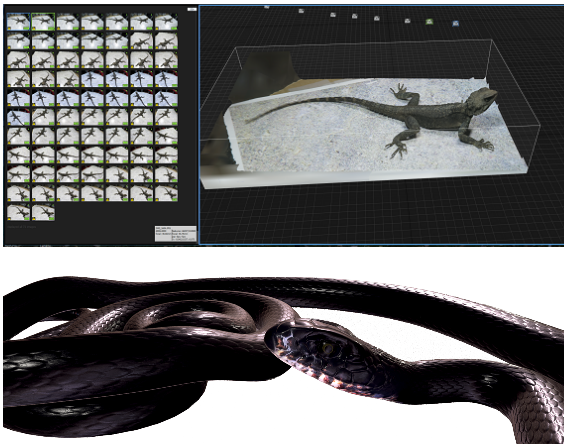

Figure 2. Top: Reconstructed 3D mesh of the lizard. Bottom: Our snake's 3D model.

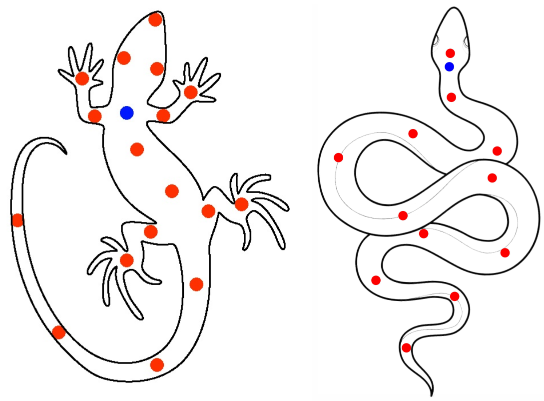

Figure 3. Demonstration of the markers' location on the reptiles.

This is done by projecting the color sampled from the photos of the known camera positions, to create a color texture map, and the corresponding normal maps, with the correct coloration and surface characteristics of the live animal. This is then applied to the partial virtual model; the textured meshes are then imported into Blender[17] and merged into a single mesh. Having the textured meshes, we proceed with the manual development of a control rig for each animal in Blender, allowing for the mesh to be deformed and animated.

Movement and behavioral acquisition

In the framework of our experiment, we use several acquisition systems to record the movement of the reptiles: (a) RGB-vision cameras, to have a reference motion, and enable behavioral labeling; (b) an optical motion capture system, to acquire the full 3D motion articulation; and (c) accelerometers, to enable behavioral recognition when reptiles are released in the wild (future work). It is important to note that reptiles make absurd and sudden movements, thus requiring to be recorded in high frame rate. This subsection describes the technologies used for acquiring the movements and behaviors of our subjects.

RGB-vision cameras Firstly, we record the animals' movements using four RGB-vision cameras, strategically placed to cover the capturing volume. More specifically, we use one fixed top view (GoPro HERO 7), two fixed side views (Canon EOS 60D and Canon EOS 7D Mark II) and one movable hand camera (Canon PowerShot SX40 HS). Cameras were recording at 30 fps (GoPro at 60 fps), with a resolution of 1920×1080.

Optical motion capturing In addition, we use a twelve-camera passive motion capture system (the Optitrack Flex 3 cameras, with resolution at 640x480). The system uses markers that are coated with a retro-reflective material to reflect light that is generated near the camera's lens. Note that these markers are firmly attached using a non epoxy glue on the reptile's body. The placement of the markers on the body was strategic, with at least one attached at each limb segment, including the head, body, legs, and tail. Figure 3 shows an illustration of the optical marker placement (in red) in our experiment. This kind of marker placement is significant so that these points can be easily and accurately located by the cameras. For the lizard, we used a total of 17 facial markers (3 mm diameter), while for the snake we used 12 medium-sized markers (14 mm diameter). The cameras operate at high frequency (at 100Hz), able to capture the position of any number of bright spots from the reflective markers. Prior to motion capturing, we calibrated the cameras, obtained their positions, and measured the lens distortion of each camera. The subjects are then released in an enclosure setup (manually constructed for the purpose of this research), and

[17] https://www.blender.org/

moved freely within the specified space; note that we added objects in the space to replicate a natural environment setup. The 3D position of the markers is then estimated using triangulation, requiring though that at least three cameras have direct view of their reflected light. The markers are tracked over time, and used to reconstruct a complete 3D pose of the reptile's body.

Accelerometers Finally, we use small-size accelerometers (AXY-4 of Technosmat) to acquire acceleration imprints for every movement and behavior recorded during our experiments; we collect these data to enable future research, whereas accelerometer measurements will be matched with high-quality motion capture data to identify specific behaviors when reptiles are released in the wild. Each animal (lizard and snake) was equipped with one accelerometer attached using 3M Vetbond Tissue Adhesive at the dorsal surface of the neck. Following bioethics rules, e.g., [27], the mass of the attached device should be less than 10% of the animal's body mass (lizard: 50 g; snake: 810g); our accelerometers weigh no more than 3g. The accelerometer position was carefully selected to allow the device to record even the smallest body movement, while simultaneously minimizing the discomfort of the animal, and thus allowing an unobstructed behavior [28]. Accelerometers are configured to a sample rate of 100 Hz, sensitivity of 2g, and a resolution of 8 bits. Prior to attaching them to the animals, accelerometers are calibrated to the three-axis.

Motion data processing

The data acquired from the RGB-vision cameras and the accelerometers need no further processing. For the scope of our 3D motion articulated reconstruction, we first need to label and denoise the optical motion capture data, and then bake animation.

Labeling Labeling data obtained from motion capture techniques is generally a time-consuming and yet a fundamental part of 3D model production. In this work, we manually create the correspondence between marker location and reptile body part on a per-frame basis. Figure 4, shows an instance of the snake's position (left) and the corresponding marker locations in 3D space (right), after labeling.

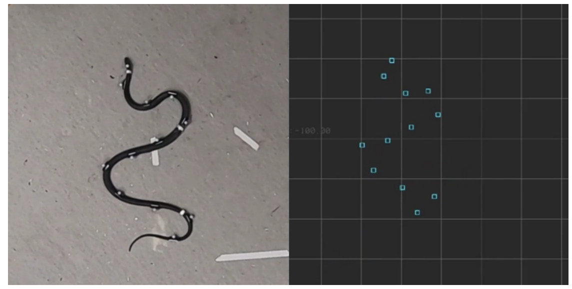

Figure 4. Display of an instance during capturing the snake and the corresponding data collected by the markers.

Cleaning data Optical motion capture data require that each marker is visible to at least three cameras so as to unambiguously establish its 3D position. However, reduced marker visibility, due to occlusions by other elements in the scene, is a common phenomenon during capturing. This requires data cleaning, and filling-in the gaps. The practice of cleaning data also applies to swapping, where instances of marker locations and labels get mixed; manually resolving these issues is a time-consuming task. Recent deep learning methods for data denoising [29], [30] cannot be enforced here since they require large dataset of clean data for training purposes. To alleviate the manual effort, we implement an iterative framework, in the context of the FABRIK algorithm [31], estimating the missing positions. More specifically, we create a kinematic chain, assuming that the distance between two consecutive markers remains stable. Thus, the FABRIK inverse kinematic solver is applied, in an iterative forward and backward manner, to position the missing markers to an estimated location, subject to rigid body constraints.

Animation baking The last part is baking the animation to the rigged skeleton, according to the captured motion of the markers. We use Autodesk MotionBuilder[18] to implement this operation. Having the data which reflect the markers' locations on the real reptiles, we define control nodes to be driven by the motion capture data.

[18] https://www.autodesk.com/motionbuilder

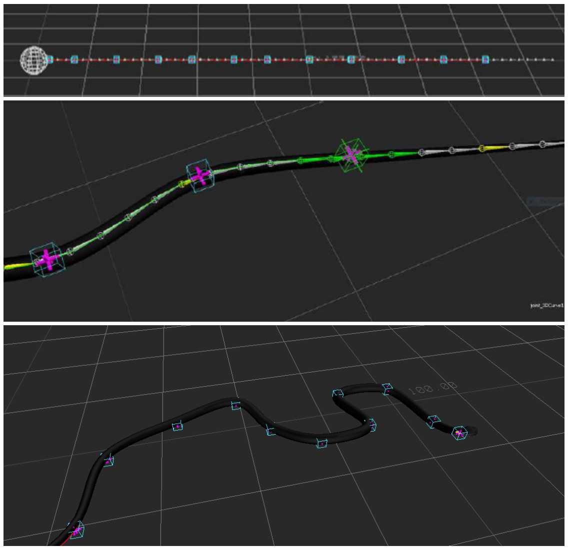

Figure 5. Display of control nodes (top), illustration of SplineIK applied to the control signals (middle), and the results of the assignment of control nodes to skeletal joints to achieve movement according to marker data over time (bottom).

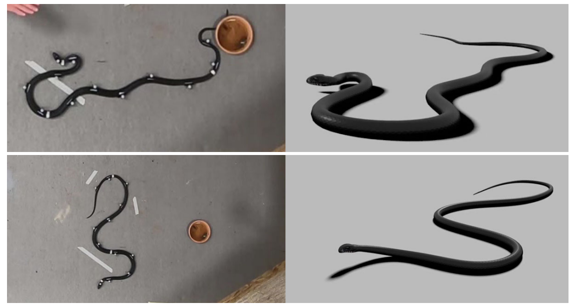

Figure 6. Illustration of two instance of mesh and movement reconstruction of the snake.

Figure 7. Our 3D Virtual Museum's Homepage.

Such nodes are placed on the corresponding joints which match the markers' positions (see Figure 5, top). Then, we activate splineIK constraints to apply the simulation of the obtained motion to the rest of the models' joints, as displayed in Figure 5 (middle). The shape of the splineIK is regulated by the control nodes, which are arranged in a parent-child setting, where the head corresponds to the parent, and the tail is the end-child. Figure 5 (bottom) demonstrates the end result of such process, while Figure 6 shows two instances of mesh and movement reconstruction of the snake, and the corresponding real pose.

Behavioral Analysis

All the acquired and processed data has been synchronised, segmented and labeled with their corresponding behavior by biology experts. In particular, we identify 10 behaviors for the lizard, and 10 for the snake. Provided that we have these pairs of motion capture data and accelerations, our work paves the way for future research to perform behavior identification, using low resolution sensors (e.g., just the accelerometer readings). This important capability may allow for the documentation of reptile behaviors in the wild, by merely attaching accelerometers to the animals, mapping their readings to the motion capture equivalents, and finally to the corresponding behaviors. All of this can uncover sides of reptiles' idiosyncrasies which, among others, can potentially help for the species preservation.

VIRTUAL MUSEUM

One of the main deliverables of our work is the production of a virtual museum of 3D reptile models. This 3D virtual museum is housed at the "Cyprus 3D Reptiles" website, which can be accessed through http://3dreptiles.cs.ucy.ac.cy/. The museum hosts visualizations of the reptiles in remarkable clarity and realism, aiming to enhance the visitor's experience in terms of information and interaction.

The online repository

The scope of the museum's design is to captivate the interest of the visitors, especially younger generations, by creating a user-friendly and interactive environment. Figure 7 illustrates the homepage of our website, which states the motivation and inspiration behind our study. Our web platform also contains information about the project, the associated partners, our team, frequently asked questions, and contact information.

In addition, there is an overview of the processes we followed.

The main exhibition of our virtual museum can be accessed through the "our reptile" page. Currently, the page contains the 3D models of two reptiles. Navigating through the page, users can explore the 3D textured model, the behaviors, and movements of the two subjects. It also refers to the Sketchfab[19] application, which allows the visitors to examine the animated avatar closely, by zooming in/out, rotating the avatar and observing the animated reptile. Apart from the 3D environment, through the Sketchfab application, visitors can visualize our models in VR and AR, as well (see Figure 8). We claim that inspecting the 3D models using the VR/AR functionalities offers a more unique experience and gives emphasis to the quality and realism of our results. The page also displays metadata information, carefully selected to enhances the educational impact of the website, while other visual material exhibited (e.g. photos) allows for further inspection and comparisons. For visitors willing to gain access to the various formats of data, we will provide links, where the data can be downloaded under a Creative Commons Attribution-ShareAlike 3.0 Unported License.

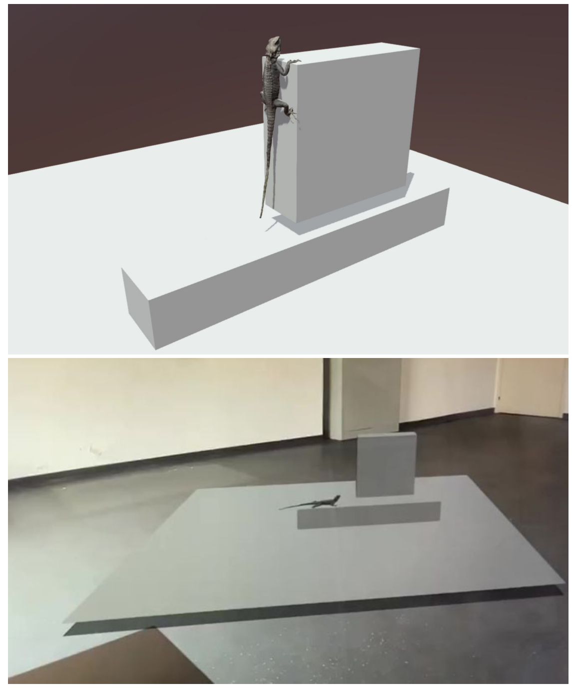

Figure 8. Example of our VR (top) and AR (bottom) applications.

Other educational tools

To further add to the learning experience of the audience, we develop two educational tools, namely an AR application, and a holographic pyramid. For these specific educational tools, in addition to our two models, we also have 13 more 3D models of different scanned Cypriot species which are not, however, animated. The complete list of available virtual model can be seen in the Supplementary material.

AR application: The AR application, available to download at http://mirror3dlab.com/apps/TerraCypria.apk, currently works only on Android operating systems. Users can visualize the animal model by directing their mobile phone camera toward a given pattern; an image with the animal's texture that is being recognized. The application then identifies the reptile species, augments the corresponding model, and projects it to the surface. Currently the application works on specifically developed patterns that are based on the dorsal coloration of Cyprus reptiles (please refer to the supplementary posters). The users can also interact with the animal by rotating their phone around the augmented model or using their finger on the screen of their mobile phones. Close-up view can be achieved by moving the phone closer to the QR pattern. This enables an interactive way to portray the reptiles and make it accessible to wider range of interested audience. Figure 9 (top) shows an example of the AR application on a live demonstration.

Holographic pyramid: Additionally, we develop a custom-made holographic pyramid, specifically designed for the needs of this project. The application operates on a two monitor-mode: the controller-view, that the instructor can have on the computer or laptop running the application, and the projection-view, that portrays different view angles of the animal in the glass pyramid structure (Figure 9, bottom). The TV view showcases the same animal as the control view but in four angles, and was achieved by developing multiple render textures in Unity3D Game Engine. Interaction is achieved through a computer mouse that users can use to rotate and zoom in/out the

[19]https://sketchfab.com/

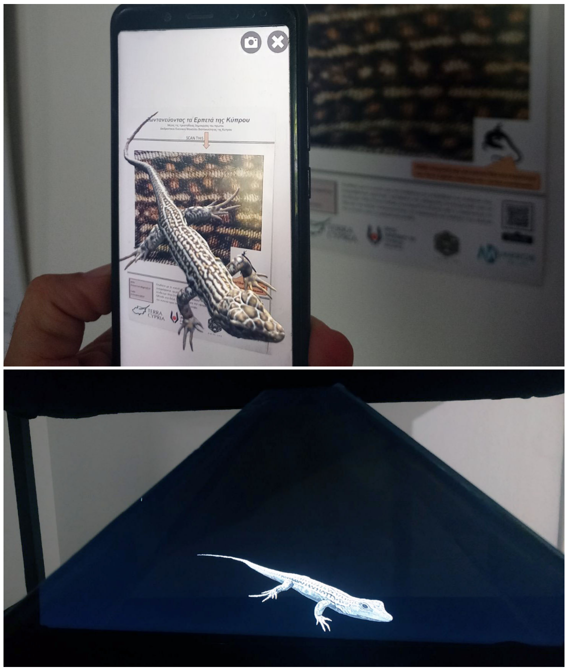

Figure 9. Our educational tools: the AR app on a live demonstration (top); and the holographic pyramid on display (bottom).

projected reptiles. This allows the dissemination of the subjects in a more sophisticated manner, which attracts the interest of audience adding an entertaining aspect to the educational material (edutainment approach) [32].

USER STUDY AND DISCUSSION

We conduct a user study to evaluate various aspects of our 3D virtual museum, and its educational impact. 114 participants attended an online survey, leading to 90 valid responses, after discarding incomplete questionnaires. We asked participants to navigate through the 3D virtual museum, engage with the two 3D models of the lizard and snake, and experience the VR/AR applications (if possible) of those models.

To ensure a fair evaluation, we attempted to reach a diverse participating audience: we collected data from 59 males and 31 females from various age groups (*18-25:* 51, *26-35:* 16, *36-50:* 20, *51-60:* 3), coming from 16 countries, using various devices and internet explorers, and having different backgrounds in terms of VR/AR experience. 72 users were engaged only with the 3D environment, 5 only with VR, 3 with AR, 4 with 3D/VR, 2 with 3D/AR, and 4 with all the technologies 3D/VR/AR. Note that, 24 participants classify themselves as "experts" on reptiles (≥ 8 in an 11-Likert scale), when asked to rate their knowledge about reptiles on a 0-10 scale (0 - No knowledge at all; 10 - Expert).

Survey set-up

Our main goal is to assess the ease of use and usefulness of our virtual museum. We formulate three hypotheses that we believe will help to shed some light on the ease of use and usefulness of our museum analogous to the logic behind the work of [14]. For the purposes of our hypothesis declaration, we use the concepts of effort expectancy (EE) and performance expectancy (PE). Venkatesh *et al.* [33] defines EE as "the degree of ease associated with the use of the system", while PE as "the degree to which an individual believes that using the system will help him or her to attain gains in job performance". Having stated those concepts, we declare our hypotheses:

- *Hypothesis 1 (H1)*: The Virtual Museum does not negatively affect the EE.
- *Hypothesis 2 (H2)*: The 3D aspect of the Virtual Museum has positive effects on PE.
- *Hypothesis 3 (H3)*: The Virtual Museum can depict realistic reptiles and reptile behaviors.

We proceed to ask three rounds of targeted sets of questions to help us accept or reject our three hypotheses. The questionnaires for all hypotheses contain 11-point Likert items.

The first set of questions focuses on usability and aims to help assess the ease of use of the museum. We encourage participants to spend some time familiarizing themselves with the website. After that, they respond to these which help evaluate navigation, interaction and overall ease of use. The relevant questionnaire can be found in Table 1.

Following the usability evaluation, we test our second hypothesis relating to PE. For this, we urged users to engage with the 3D environment, and/or the VR/AR functionalities of our models (provided they have the necessary equipment). We specifically selected these questions to reveal how helpful this particular environment is in terms of learning and how useful the experience was. To further evaluate the usefulness of our

Table 1. Questionnaire for testing H1.

H1: *The Virtual Museum does not negatively affect the EE.*	
H1.1	How familiar are you with 3D/Virtual/Augmented Reality?
H1.2	What has been your level of interaction with 3D/Virtual/Augmented Reality as educational material?
H1.3	How confident are you using and navigating through webpages?
H1.4	Navigate through the website's 8 pages. Did you encounter a lot of difficulties?
H1.5	Interact with the 3D models of the two reptiles. Was the interaction too demanding?
H1.6	Did you need any assistance using the website?
H1.7	Overall, how easy was the website to use?

Table 2. Questionnaire for testing H2.

H2: *The 3D aspect of the Virtual Museum has positive effects on PE.*	
H2.1	How much knowledge do you have about reptiles?
H2.2	What has been your level of interaction with reptiles in real life?
H2.3	Using the webpage, did you feel stimulated (eager/enthusiastic)?
H2.4	Did you learn interesting information?
H2.5	Did the webpage/VR/AR application provide you with a unique experience?
H2.6	How easy is it to understand the morphology and geometry of the reptile using our 3D virtual museum compared to The Reptile Database (e.g.: size, shape, proportions)?
H2.7	How easy is it to understand the features of the reptile using our 3D virtual museum compared to The Reptile Database (e.g.: texture, thorns, color, patterns)?
H2.8	How easy is it to understand the motion and behavior of the reptile using our 3D virtual museum compared to The Reptile Database?

Table 3. Questionnaire for testing H3.

H3: *The Virtual Museum can depict realistic reptiles and reptile behaviors.*	
H3.1	When interacting with the 3D models, how realistic are the reptiles?
H3.2	How natural would you characterize the reptiles' movements (did you have a realistic feeling of the reptiles' movements)?
H3.3	How easy is it to understand the morphology and geometry of the reptile using our 3D model compared to the still image (e.g.: size, shape, proportions)?
H3.4	How easy is it to understand the features of the reptile using our 3D model compared to the still image (e.g.: size, shape, proportions)?
H3.5	How natural would you characterize the lizard's movements (did you have a realistic feeling of the lizard's movements)?
H3.6	How easy is it to understand the movement and behavior of the lizard using our 3D model compared to the video?
H3.7	How natural would you characterize the snake's movements (did you have a realistic feeling of the snake's movements)?
H3.8	How easy is it to understand the movement and behavior of the snake using our 3D model compared to the video?
H3.9	Based on the two examples above, do you think that the 3D models reflect realistically the movements and behaviors of the two reptiles?

environment, we direct the user to visit "The Reptiles Database" website, and then asked them to observe the corresponding reptiles, for comparison purposes. Table 2 lists the questions related to this hypothesis.

Finally, we assess our third hypothesis by asking questions specific to the realism of the 3D models, and the naturalness of motion. Respondents were also asked to state their preference in terms of the features of the species (e.g. texture, shape, behavior) compared to pictures and videos. For this purpose, participants were exposed to a series of short videos, displaying the animated avatars and the corresponding video recording of the animal, side by side. Table 3 presents the set of questions concerning H3.

Discussion

The results of the average responses to the set of questions concerning H1 (Table 1) are shown in Figure 10 (red). The first questions (H1.1& H1.2) demonstrate that, on average, the participants of the survey are vaguely familiar with 3D/VR/AR environment (avg.: 4.74) but have not used it regularly for education purposes (avg.: 2.62). Even though they had limited experience, results of H1.5 provide evidence that they could interact with the 3D environment easily. Besides that, the navigation through the webpage and the webpage environment in general, was easy to use (H1.4, H1.6 & H1.7) especially for users with experience in handling such webpage environments (H1.3). Therefore, our system was easy to use and so we can conclude, in this rather limited study, that our virtual museum did not negative affect

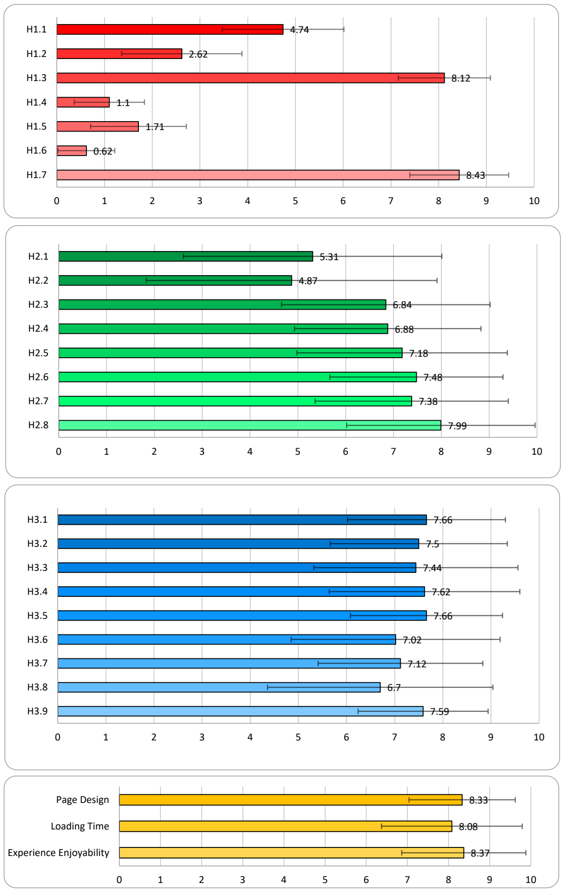

Figure 10. Results for the H1 (red), H2 (green), H3 (blue), and user experience (yellow) questionnaires. Numbers at the end of the colored bars indicate the mean value, and the gray bars the standard variation.

EE (H1 is valid).

The second set of questions, described in Table 2, was used to assess H2 with final results presented in Figure 10 (green). When users were asked about the usefulness of our virtual museum (H2.3, H2.4 & H2.5), via questions regarding eagerness, usefulness of information and uniqueness of experience, they gave a positive feedback which, however, was not strongly positive (avg.: 6.84, 6.88 & 7.18). We also found that users were vaguely familiar with reptiles (H2.1, H2.2) in terms of knowledge and interaction (avg.: 5.31, 4.87). This lack of previous experience could affect their ability to judge the usefulness of our system so we introduced comparison questions against another database to give them more context about the state-of-the-art in this domain. The results of such comparison questions (H2.6, H2.7 & H2.8) largely favoured our museum (avg.: 7.48, 7.38 & 7.99), showing that it is more useful to users than works like “The Reptile Database”. Thus, these responses leads us to believe in the usefulness of our system, providing evidence in favour of the validity of H2.

For the purposes of evaluating H3, we display the user results of the relevant questions (Table 3) in Figure 10 (blue). These results indicate that, our museum achieves a high level of realism (avg.: 7.66 & 7.50), both regarding the naturalness of our reptiles’ appearance and their movements (H3.1 & H3.2). For more detailed analysis, we asked participants to compare our models with the relevant images and videos. The user responses reveal a certain level of preference to our model both compared to images (H3.3 & H3.4) and to videos (H3.6 & H3.8). After asking the participants to compare images/videos with our model, we redirected their attention to the realism of our reptiles (H3.5, H3.7 & H3.9), which again showcases that our reptiles are more realistic (avg.: 7.44, 7.12 & 7.59), suggesting that H3 is conceivably valid.

A final set of questions measuring user experience and the analogous average responses is displayed in Figure 10 (yellow). The figure clearly shows that their experience was pleasant, which ensures they had the necessary comfort to answer the questions honestly.

CONCLUSION

We have designed and developed a publicly accessible repository of high quality 3D reptile models, with a variety of motions and different behaviors. In this early version, we have acquired movements from two Cypriot species, a lizard and a snake, using an optical motion capture system. These specimens have been documented with holistic information, and organized in a metadata schema. This enables the study of their behavior through the collected digital data, interactive navigation, and could drive the development of educational tools, and methods for behavior recognition. We claim, through a user survey, that 3D display and interaction has an advantage over virtual archives of images or videos. The survey also revealed that our museum is both useful and easy to use. Aiming to demonstrate further possibilities of such data, we have presented two tools:

a holographic pyramid and an AR application.

Limitations
Despite the many benefits of our system, there are some limitations concerning our work. Regarding the motion capturing process, the marker positions do not accurately represent the position of the joint of the reptiles. The body and skin of the animals creates some distance between markers and joints, resulting in marker offsets which make the motion appear more drastic than it really is (for instance, see Figure 4). Moreover, a limitation specific to the lizard's motion capture process stems from the need to use small sized markers. Theses markers require cameras to be placed very close to the subject, thus reducing the capturing volume. Finally, since we cannot place marker at the end of the tails, there is the need to simulate the movement of the end point of the tail (the kinematic chain between the last marker and the end point).

Future Work
Our system is both reusable and extensible, facilitating various avenues for future research. One such direction is motion capturing more species of animals, including several subjects of individual species, with different behaviors. In addition, a promising step is to work towards developing algorithms for motion synthesis. Having pairings of data (e.g., high resolution optical data with low resolution accelerometers), we can train deep networks to identify and reconstruct behaviors in natural environments, only requiring an accelerometer to be attached to the reptile. This may help in the understanding of the reptile habitats, leading to important discoveries regarding animals' lives that is vital to wildlife preservation. The content and structure of our metadata can be used for indexing, analysis and identifying correlations between our data, and other databases. Lastly, our work motivates the development of educational virtual games, highlighting the importance of advancing current educational tools to keep up with latest technologies, and bring wildlife closer to the younger generation.

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